The harzburgite member of an ultramafic body in granulites, Lake Kondinin, Western Australia

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Abstract

An ultramafic body is enclosed in granulite facies metamorphic rocks, and is composed of lherzolite and harzburgite units. The harzburgite and some associated strongly feldspathic rocks are discussed in this paper. Their petrography is described, and chemical analyses of rocks and their constituent minerals are presented. The harzburgite appears to have been emplaced during the metamorphism. Deformation of orthopyroxene grains in the harzburgite suggest that it was partly crystalline during emplacement. Its chemistry suggests that it consists of two sub-units, one rather more fractionated than the other. The feldspathic rocks form small bodies of unknown form; compared with the harzburgite, they are rich in Al, Ca, Na, and, elements that are not easily accommodated in the lattices of the harzburgite minerals. The feldspathic rocks may represent either a late stage "pegmatitic" phase of the harzburgite, or be the result of an alkali metasomatism induced by later granitoid intrusive activity.

Introduction

This report further explores the theme of the author's earlier paper (Morgan 1982) concerning the emplacement of ultramafic material during high-grade metamorphism, and the retention of relic igneous structures after crystallization during the metamorphism.

Harzburgite, together with very minor bodies of plagioclase-rich rocks, are part of an ultramafic complex emplaced in high-grade Archaean gneisses (Morgan 1982), 3 km north of the Corrigin-Kondinin road, 217 km east-south-east of Perth, Western Australia (Fig. 1). The complex occurs mainly beneath a salt lake. Only very poor exposures can be seen on the western shore of the lake where, during the late 1960's, the Electrolytic Zinc Company drilled four holes into the ultramafic body. This report results from a study of diamond drill cores very kindly made available to the author by the company. The locations of the drill holes are shown in Figure 1.

In the sequence exposed by drilling (Fig. 2), harzburgite occurs "down-hole" from the felsic gneiss exposed in DDH C2 and C4, and "up-hole" from lherzolite exposed in DDH C4 and C5. The feldspathic rocks form small bodies of unknown form within the harzburgite, and consist of an anorthosite and two magnetitebiotite andesinites. As will be discussed in a later section, the harzburgite is considered to have been emplaced after the lherzolite described by Morgan (1982).

The harzburgite unit

Petrographic study of the cores of DDH C3, C4, and C5 supplemented by rock and mineral analyses, shows that the harzburgite consists of two sub-units, megacrystic harzburgite, and lenticular-textured harzburgite. Close to its contact with the lherzolite (Fig. 2), the magacrystic harzburgite has a textural variant, referred to as radial pyroxene harzburgite. DDH C2 was not examined, due to lack of time and facilities.

Petrography

Minerologically, the harzburgite consists of olivine, orthopyroxene, magnetite, and minor quantities of phlogopite. Averages of modal analyses from each of the sub-units are shown in Table 1. Modal analyses of individual samples are considered meaningless and not tabulated, because of the irregular distribution through the core of orthopyroxene megacrysts and lenticular aggregates.

Serpentinization of both olivine and orthopyroxene is almost complete in DDH C3. The original mineralogy can, however, be easily deduced from the textural and pseudomorphous appearance of the serpentine. In DDH C4 and C5, serpentinization affects between 20% and 80% of the samples examined. In the uppermost 80 m to 90 m of all the cores, serpentinized harzburgite is very strongly silicified and ferruginized.
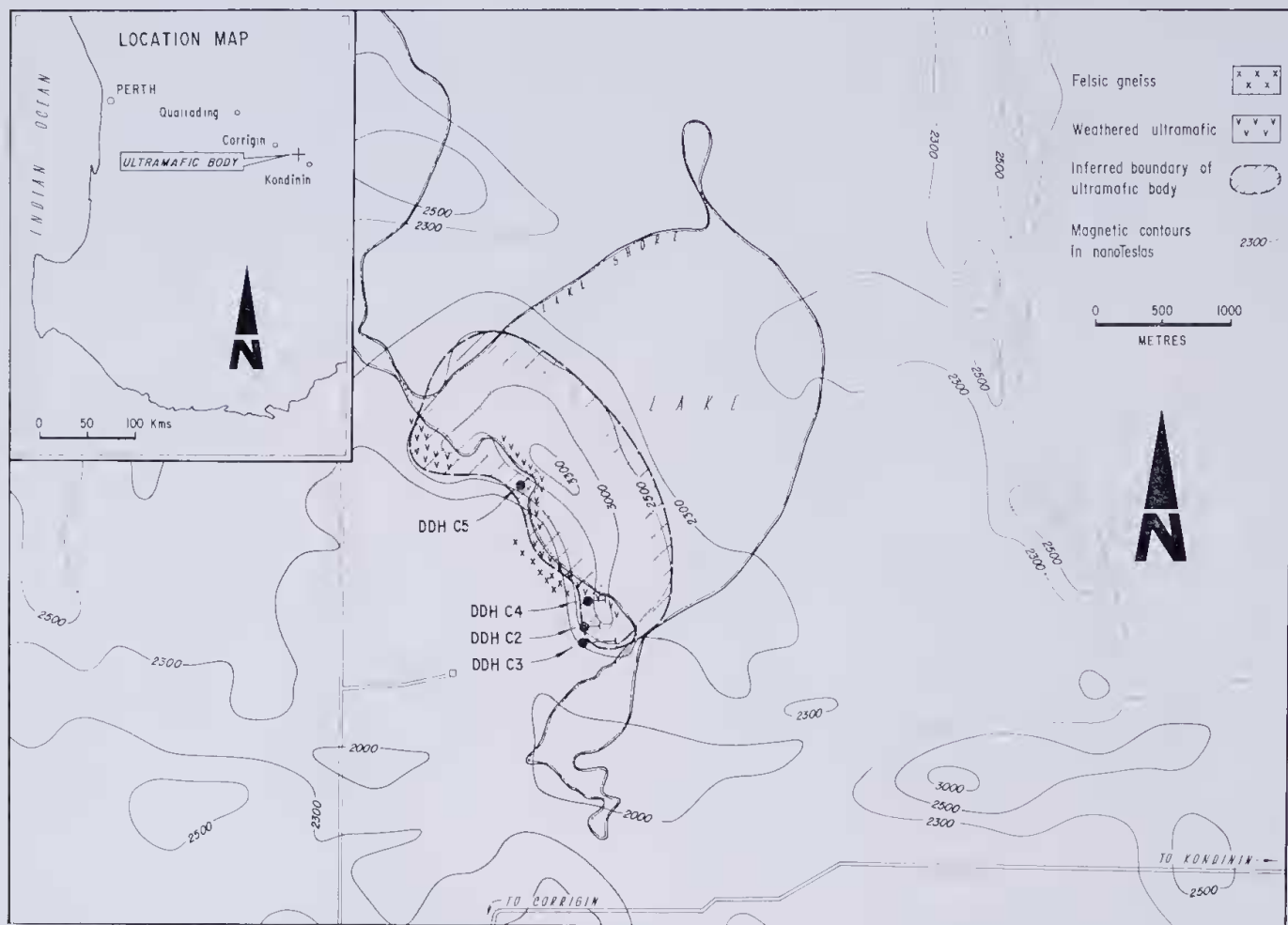
Figure 1.—Simplified aeromagnetic anomaly map of the ultramafic near Lake Kondinin. Reproduced by permission of the Electrolytic Zinc. Co. of Australasia. *Inset*: Location map, South Western Australia.

Megacrystic harzburgite.

The extent of the magacrystic harzburgite is shown in Figure 2. In this rock, megacrysts of orthopyroxene, ranging up to 20 mm long, are enclosed in a matrix of polygonal olivine and orthopyroxene grains that have an average diameter of 1 mm. In the southernmost drill hole (C3) the megacrysts are euhedral prismatic, and have a preferred orientation. Although they are almost completely serpentinized, inset relics of orthopyroxene in any one megacryst are in complete optical continuity, indicating that they are unstrained. Relics of olivine in the serpentinized matrix likewise show no evidence of deformation.

However, in DDH C4 and C5, the orthopyroxene megacrysts are commonly strained, with mosaic substructure and, more rarely, kink-banding. Very often they are polygonized to aggregated of strain-free grains on their margins. Particularly in DDH C5— the northernmost hole—the megacrysts tend to be almost completely polygonized, with the constituent grains of the aggregates showing a preferred orientation. In the matrices of these rocks, olivine and orthopyroxene are almost entirely unstrained. Where

not obscured by serpentinization, the matrix texture is polygonal. with the grains having curvilinear to straight boundaries meeting in triple points. Here and there, incomplete crystallization equilibrium is suggested by sub-amoeboid grain boundaries.

Magnetite occurs as granular to sub-amoeboid grains, 0.2 to 1 mm in diameter. Phlogopite, where it occurs, forms subhedral, nearly colourless books that tend to have a preferred orientation parallel to that of the orthopyroxene megacrysts.

Table 1

Harzburgite Modal Analyses

	Mega-crystic	Radial Pyroxene	Lenticular	Average
Olivine ...	67·7	72·2	69·3	69·7
Orthopyroxene	24·5	21·8	20·5	27·3
Magnetite	5·8	3·9	5·9	5·2

Radial pyroxene harzburgite is a textural variant of megacrystic harzburgite, because they are geochemically similar to each other, whereas the lenticular-textures harzburgite shows significant differences in both composition and texture. The radial pyroxene harzburgite is adjacent to the contact of harzburgite with lherzolite in DDH C4 and C5. It contains sub-radial growths of orthopyroxene measuring up to 15 cm across. Within the growths, sub-radiating, thin orthopyroxene grains are elongated nearly parallel to their crystallographic c-axes, their grain boundaries being finely sutured. Some mosaic sub-structure is seen in places, but otherwise there is little evidence of deformation. The associated olivine is strongly serpentinized; relic grains suggest that their sizes range up to 10 mm, that they have an amoeboid shape, and that they are entirely unstrained.

Figure 2.—Schematic diagram, from diamond drill hole data, of the relationships between the megacrystic, lenticular, and radial pyroxene harzburgite.

Lenticular-textured harzburgite.

The core samples display a lenticular-banded appearance. The lenticles—composed of orthopyroxene—measure up to 1.5 cm wide by 4 cm long, and are enclosed in an olivine-rich matrix. In some cores, particularly around 100 m depth in DDH C5, the lenses form tight, isoclinal folds.

In section, the lenses are seen to consist of aggregates of polygonal orthopyroxene grains showing no strain whatsoever. The matrix olivine, where it is not strongly serpentinized, is also polygonal and strain-free. The very sparse phlogopite flakes have a preferred orientation parallel to the lenses.

Chemistry

Major and some minor element analyses of five samples of harzburgite are presented in Table 2. Each analysis was made from a representative sample taken from 1.5 m lengths of core, in an attempt to balance out the irregular distribution of orthopyroxene.

The harzburgite samples consist essentially of SiO_2, iron oxides, and MgO, with only very minor quantities of the other oxides when compared with ultramafics in alpine-type bodies (eg. Loney *et al.* 1971), high temperature peridotites (eg. Green 1964), ultramafic nodules (eg. Carswell and Dawson 1970), komatiitic peridotites (eg. Nesbitt and Sun 1976), and the ultramafic portions of layered gabbroic intrusives (eg. Hess 1960, Hall 1932).

There are differences between the lenticular-textured and megacrystic sub-units of the harzburgite. The lenticular-textured harzburgite is poorer in Cr, Ni, Co, V, and Zn. However, the most significant difference is in the Fe/Mg ratios. In the megacrystic sub-unit, these range between 0.55 and 0.69, distinctly higher than the value of 0.45 in the lenticular harzburgite. The differences suggest that the sub-units represent two different—though possibly related—intrusives, one of which (the megacrystic sub-unit) is rather more fractionated than the other.

The least differentiated members of the lherzolite unit's cycles all contain more Al_2O_3 and CaO (Morgan 1982). Their Fe/Mg ratios (0.57-0.70), however, fall within the range of the megacrystic harzburgite.

Mineral chemistry

Electron microprobe analyses of olivine, orthopyroxene, and magnetite are presented in Tables 3, 4, and 5 respectively. All analyses were carried out by the author with the W.A. Institute of Technology's Seimens Etec Microprobe analyser, using an accelerating voltage of 20 kV, a specimen current of 0.25×10^{-7} amps, and a 1 - 2 um beam diameter. X-ray intensities were converted to oxide percentages using the Magic IV programme.

Olivine (Table 3)

The Mg/(Mg + Fe) ratios range between 0.90 and 0.95, i.e., within the range of olivines from alpine-type ultramafics, and distinctly more Mg-rich than those from the lherzolite unit (Morgan 1982), as will be seen from Figure 3, or from the layered intrusives (eg. Green 1964, Cameron 1978). Olivines from the lenticular-textured harzburgite contain more Mg than those from the megacrystic sub-unit.
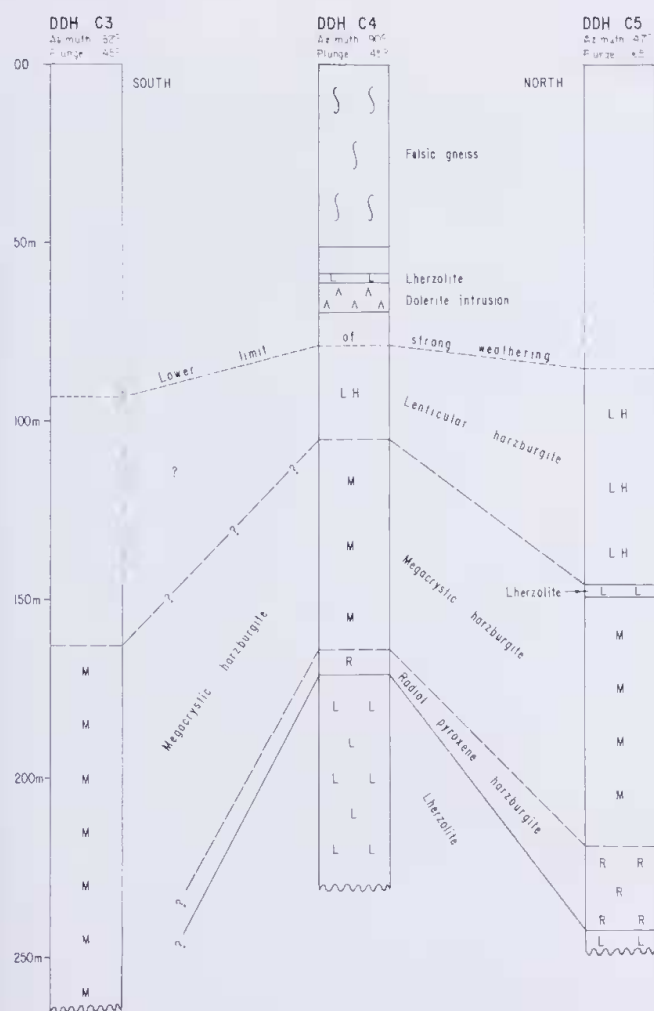
Table 2

Analyses and Norms of the harzburgites

	Megacrystic Harzburgite			Lenticular-textured Harzburgite	
Drill Hole	C4	C4	C4	C4	C5
Depth	169·3m	156·4m	125·9m	101·7m	115·8m
SiO$_2$	36·87	38·93	40·58	41·05	36·05
TiO$_2$	0·04	0·07	0·04	0·06	0·06
Al$_2$O$_3$	0·37	0·38	0·32	0·40	0·64
Fe$_2$O$_3$	7·98	11·71	8·88	6·77	9·04
Cr$_2$O$_3$	0·95	N.D.	1·07	0·83	0·84
FeO	7·49	8·58	7·09	6·51	4·81
MnO	0·22	0·18	0·20	0·19	0·28
MgO	34·12	36·03	32·33	35·95	37·06
NiO	0·29	N.D.	0·29	0·22	0·25
CaO	0·30	0·13	0·18	0·24	0·03
Na$_2$O	0·04	0·03	0·06	0·05	0·03
K$_2$O	0·04	0·05	0·03	0·09	0·01
P$_2$O$_5$	0·002	N.D.	0·01	0·01	0·01
Loss	10·77	3·60	8·11	6·85	11·00
Total	99·48	99·69	99·19	99·21	100·11
Co	248	N.D.	249	201	217
Cr	6 510	N.D.	7 348	5 678	5 722
Ni	2 300	N.D.	2 250	1 700	2 000
V	23	N.D.	17	8	12
Zn	130	N.D.	135	80	75
Fe/Mg	·554	·685	·601	·451	·450
or	0·22	0·28	0·17	0·56	0·06
ab	0·37	0·26	0·52	0·42	0·26
an	0·70	0·64	0·50	0·58	0·08
C	....	0·02	. .	....	0·45
di— Wo	0·33	....	0·14	0·23	....
en	0·27	....	0·11	0·19	....
fs	0·03	....	0·001	0·01	....
hy— en	27·76	31·74	45·74	37·24	25·82
fs	2·35	2·23	3·18	2·61	0·42
ol— fo	39·90	40·63	24·29	36·53	46·59
fa	3·73	3·14	1·85	2·83	0·86
il	0·08	0·14	0·08	0·12	0·12
mt	11·58	16·97	12·87	9·82	13·12
ct	1·41	....	1·57	1·23	1·23
ap	0·003	....	0·02	0·02	0·02
Loss	10·77	3·60	8·11	6·85	11·00
Total	99·50	99·65	99·15	99·24	100·03

Analyst: S.G.S. Australia Pty. Ltd., Perth.

N.D.—No Data

The distribution of Mg and Fe between olivines and their co-existing orthopyroxenes is fairly uniform (Fig. 3), the values of $K_D \dfrac{Fe/Mg \; opx}{Fe/Mg \; ol}$ having an average of 1.05 and a range of 0.9 to 1.2. The values are close to those of Morgan (1982), Frost (1975), Challis (1965), and Green (1964).

Ti, Al, Cr, Ca, Na and K are low or absent, Mn is low, and Ni shows, as one would expect, a preference for olivine over orthopyroxene.

Orthopyroxene (Table 4)

The Mg/(Fe + Mg) ratios range between 0.895 and 0.95. Like the olivines, these values are distinctly higher than those of the lherzolite unit (see Fig. 3), which range between 0.79 and 0.89. Orthopyroxenes from the lenticular-textured sub-unit are more Mg-rich than those of the megacrystic harzburgite.

The harzburgite orthopyroxenes are low in Al, Ca, Cr, and Ti, when compared with those in the lherzolite unit (Morgan, 1982), alpine (eg. Loney et al. 1971), nodule (eg. Boyd et al. 1976, Dawson et al. 1970), and layered intrusion harzburgites (Cameron 1978). This, of course, is a condition imposed by the host rocks, which are themselves poor in these elements.

Magnetite (Table 5)

Total iron was analysed as Fe$_2$O$_3$; Fe^{+2} and Fe^{+3} were calculated assuming ideal stoichiometry. The magnetite, like that in the lherzolite unit (Morgan 1982) is chromiferous, with Cr being concentrated in this mineral, very little being in the co-existing orthopyroxene. Al$_2$O$_3$ ranges between 0.70% and 2.18%. Al$_2$O$_3$ is very low in the harzburgite rock analyses (Table 2), but, like Cr. is concentrated in magnetite rather than in the associated silicate phases. MgO ranges between 0.4% and 4.46%; Mg/(Mg + Fe^{+2}) ratios tend to be rather higher in the lenticular-textured harzburgite sample when compared with those of the megacrystic sub-unit.

Table 3

Electron microprobe analysis of olivine.

Analyst: W. R. Morgan

				Megacrystic Harzburgite				Lenticular-textured Harzburgite			
					DDH C4						DDH C5
Depth				169·3 m	156·4 m	146·9 m	143·8 m	101·7 m	99·7 m	94·5 m	115·8 m
SiO₂	....	....	....	42·14	40·49	40·23	40·70	41·85	41·82	41·79	39·80
TiO₂	....	....	....	Nil	0·05	0·02	0·02	Nil	Nil	Nil	0·04
Al₂O₃	....	....	....	Nil	0·13	0·09	Nil	0·20	0·10	0·19	0·19
Cr₂O₃	....	....	....	Nil	0·01	0·03	Nil	0·05	0·06	0·01	0·01
FeO	....	....	....	9·35	10·21	9·37	9·09	6·92	7·36	6·43	4·47
MnO	....	....	....	0·25	0·21	0·19	0·23	0·19	0·20	0·14	0·27
NiO	...	....	....	0·56	0·49	0·32	0·33	0·30	0·52	0·49	0·44
MgO	....	....	....	47·10	49·11	49·37	50·05	50·95	50·06	51·38	53·75
CaO	....	....	....	Nil	0·01	0·01	0·02	0·03	0·01	Nil	Nil
Na₂	....	....	....	Nil	0·01	0·14	Nil	Nil	0·08	0·08	0·08
K₂O	....	....	....	Nil	Nil	Nil	Nil	Nil	Nil	0·01	0·04
Total ...	....	....		99·40	100·73	99·77	100·43	100·48	100·22	100·53	99·09

Numbers of ions on the basis of 4 oxygens

|											
Si	....	....	....	1·034	·990	·989	·992	1·007	1·012	1·004	·968
Al	....	....	....	....	·004	·003	....	·006	·003	·005	·006
Ti	....	....	....	....	·001	·001	·001	....	....	. .	·001
Fe	....	....	....	·192	·209	·193	·185	·139	·149	·129	·091
Cr	....	....	....	Tr	Tr	·001	....	·001	·002	Tr	Tr
Mn	....	....	....	·005	·004	·004	·005	·004	·004	·003	·006
Ni	....	....	....	·011	·010	·006	·006	·006	·010	·010	·009
Mg	....	....	....	1·723	1·789	1·809	1·818	1·827	1·805	1·840	1·947
Ca	....	....	....	....	Tr	Tr	·001	·001	Tr	. .	....
Na	....	....	....	....	Tr	·007	....	....	·004	·004	·004
K	....	....	....	....	. .	....	....	..		Tr	·001
Mg	....	....	....	10·0	10·5	9·6	9·2	7·1	7·6	6·6	4·5
Fe	....	....	....	90·0	89·5	90·4	90·8	92·9	92·4	93·4	95·5
Mg/(Fe + Mg)	....			·900	·895	·904	·908	·929	·924	·935	·955
Fe/(Fe + Mg)	....			·100	·105	·096	·092	·071	·076	·066	·045
Fe/Mg	....	....	....	·111	·117	·107	·012	·076	·083	·070	·046
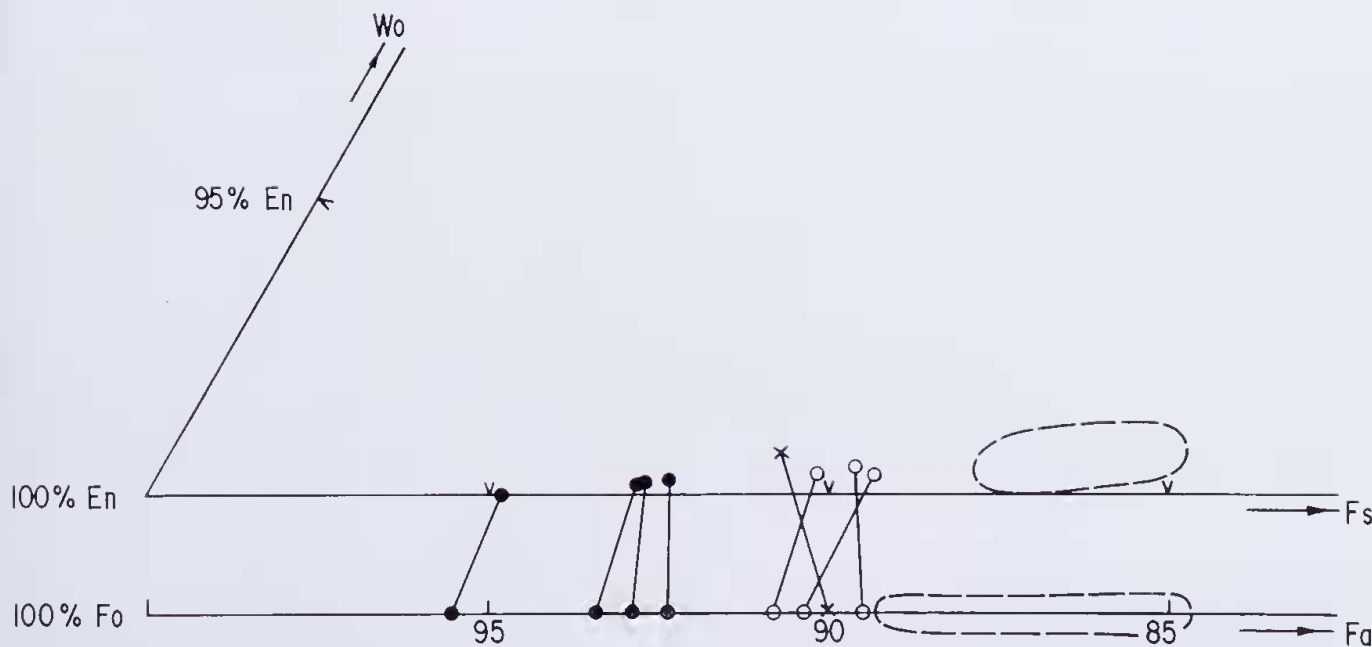
Figure 3.—Plot of co-existing olivines and orthopyroxenes. Filled Circles: lenticular harzburgites; Open Circles: megacrystic harzburgites; x: radial pyroxene harzburgite: Dashed outline areas: olivines and orthopyroxenes in the lherzolite unit (Morgan 1982).

Table 4

Electron microprobe analyses of orthopyroxene.
Analyst: W. R. Morgan

	Megacrystic Harzburgite							Lenticular-textured Harzburgite
				DDH C4				DDH C5
Depth	169·3 m	156·4 m	146·9 m	143·8 m	101·7 m	99·7 m	94·5 m	115·8 m
SiO_2	58·27	56·69	58·84	57·04	58·23	58·39	59·35	58·38
TiO_2	Nil	0·02	0·01	0·04	0·04	Nil	0·05	0·05
Al_2O_3	0·53	0·11	0·45	0·23	0·19	0·41	0·44	0·66
Cr_2O_3	0·05	0·13	0·08	0·03	0·05	0·05	0·06	0·22
FeO	6·21	7·00	7·05	6·81	4·86	5·21	4·84	3·56
MnO	0·25	0·21	0·23	0·28	0·20	0·22	0·23	0·31
NiO	0·12	0·09	0·05	0·11	0·04	0·10	0·07	0·04
MgO	34·93	34·79	33·58	35·59	35·30	36·07	35·46	36·27
CaO	0·34	0·28	0·14	0·17	0·11	0·13	0·11	0·03
Na_2O	Nil	0·07	0·03	0·01	Nil	Nil	Nil	0·05
K_2O	Nil	0·01	Nil	0·01	Nil	Nil	Nil	0·01
Total	100·70	99·38	100·26	100·32	99·02	100·58	100·63	99·38

Numbers of ions on the basis of 6 oxygens

	169·3 m	156·4 m	146·9 m	143·8 m	101·7 m	99·7 m	94·5 m	115·8 m
Si	1·993	1·997	2·019	1·969	2·009	1·989	2·013	1·997
Al^{iv}	·007	·005	...	·009	....	·011	....	·003
Al^{vi}	·014	....	·018	....	·008	·006	·018	·023
Ti	..	·001	Tr	·001	·001	....	·001	·001
Fe	·178	·204	·202	·197	·140	·149	·137	·101
Cr	·002	·004	·001	·001	·001	·002	·002	·006
Mn	·007	·006	·007	·008	·006	·006	·007	·009
Ni	·003	·003	·001	·003	·001	·003	·002	·001
Mg	1·780	1·808	1·717	1·831	1·815	1·832	1·793	1·837
Ca	·013	·011	·005	·006	·004	·005	·004	·001
Na	..	·002	·002	·001	....	....	..	·003
K	..	Tr	..	Tr	..	..	..	Tr
Mg	90·3	89·4	89·2	90·0	92·6	92·2	92·7	94·7
Fe	9·0	10·1	10·5	9·7	7·2	7·5	7·1	5·2
Ca	0·7	0·5	0·3	0·3	0·2	0·3	0·2	0·1
Mg/(Mg + Fe)	·909	·899	·895	·903	·928	·925	·929	·948
Fe/(Mg + Fe)	·091	·101	·105	·097	·072	·075	·071	·052
Fe/Mg	·100	·113	·118	·108	·077	·081	·076	·055

Table 5

Electron microprobe analyses of magnetite.
Analyst: W. R. Morgan

	Megacrystic Harzburgite							Lenticular-textured Harzburgite
				DDH C4				DDH C5
Depth	169·3 m	156·4 m	147·5 m	143·8 m	101·7 m	99·77 m	94·5 m	115·8 m
TiO_2	0·16	0·39	0·02	0·19	0·29	0·10	0·07	0·26
Al_2O_3	2·11	1·74	0·94	0·70	1·15	1·43	0·94	2·18
Cr_2O_3	13·61	7·20	7·77	5·52	12·43	9·01	7·95	8·29
Fe_2O_3	54·69	59·96	59·65	62·62	56·17	58·88	60·47	59·72
FeO	27·62	28·04	30·13	29·07	25·60	27·68	27·04	24·38
MgO	2·80	2·21	0·40	1·29	3·59	2·31	2·61	4·46
Total	101·00	99·94	98·91	99·39	99·23	99·41	99·08	99·29

Numbers of ions on the basis of 32 oxygens

	169·3 m	156·4 m	147·5 m	143·8 m	101·7 m	99·77 m	94·5 m	115·8 m
Al	·730	·616	·341	·252	·404	·507	·335	·758
Cr	3·155	1·708	1·889	1·330	2·929	2·142	1·899	1·932
$Fe^{·3}$	12·069	13·541	13·806	14·361	12·600	13·323	13·747	13·252
Ti	·035	·088	·004	·046	·063	·023	·016	·058
Mg	1·223	·988	·185	·586	1·594	1·035	1·175	1·960
Fe^{+2}	6·777	7·038	7·751	7·409	6·382	6·962	6·831	6·012

The feldspathic rocks

There are three very minor occurrences of unusual plagioclase-rich rocks within the harzburgite unit. All are intersected by DDH C5. The occurrences are:

216.3 m-215.7 m Biotite-magnetite-andesine rock.

187.7 m-187.2 m Biotite-andesine rock.

157.3 m-157.4 m Spinel-bearing anorthite rock.

Structure and relationships

A few points can be noted:

(1) There is strong alteration of the harzburgite on both sides of the anorthite rock. Such alteration occurs only on the "down-hole" side of the andesine rocks. The alteration takes the form of talcose, serpentine material that provided very little core recovery.

(2) Internally, the anorthite body is the most simple: a thin zone of anorthite rock is bounded on the "up-hole" side only by a selvage of phlogopite.

(3) The two andesinic rocks are more complex. That at 187 m has a bilateral zonation: a central zone of soft clay-sericite material is bounded either side by successive zones of biotite, biotite-plagioclase, and biotite. The occurrence at 216 m is rather less symmetrical. A central zone of incompletely recovered micaceous rock has zones of magnetite and biotite-magnetite-andesine rock either side of it. The "uphole" margin is composed of magnetite-biotite rock, and the "down-hole" side of a biotite-sericite rock which may represent a hydrothermally altered biotite-plagioclase rock.

(4) The form of the bodies is not known. Prider (1945) reported hypersthene andesine rock forming a segregation within hornblende hypersthenite at the Dangin railway cutting, 80 km north-north-west of Lake Kondinin. However, whether the Lake Kondinin occurrences are segregations or intrusive bodies is difficult to tell from the core samples available.

Petrography

Anorthite rock: 157 m. The upper marginal zone consists of crumpled, nearly colourless flakes of phlogopite that show a rough preferred orientation parallel to the contact with the anorthite rock. Accessory zircon is present.

The plagioclase rock consists almost entirely of polygonal grains of anorthite ranging between 0.1 and 1.5 mm in size. Very minor quantities of weakly pleochroic biotite are present. Irregularly zoned green to brown spinel forms grains about 0.2 mm across the triple junctions of plagioclase grains. Also present are very thin stump prisms of apatite, and grains of a metamict mineral that perhaps represents zircon.

Biotite-andesine rock: 187.2-187.7 m. The micaceous zones are composed of very pale brown, intergrown mica flakes measuring up to 3 mm across. The flakes are strongly contorted and the edges are crumpled and even fragmented.

The two zones of biotite-andesine rock are very similar. Plagioclase forms angular to amoeboid grains ranging between 0.5 and 10 mm across; in a few grains, the twin lamellae are slightly strained. Biotite is pleochroic from pale-brown to mud-brown, and forms sub-tabular to anhedral flakes that are frequently clustered, and which—particularly in the upper zone—show a preferred orientation parallel to the contacts. Accessory apatite and zircon are present.

Biotite-magnetite-andesine rock: 215.7-216.3 m The micaceous margin is very similar to that described above. The andesine rocks contain polygonal plagioclase grains 0.5 to 2 mm in size, along with amoeboid magnetite grains up to 5 mm across, and subhedral, randomly oriented books of biotite about 1 mm long. Accessory prismatic apatite and sub-rounded zircon are present.

The lowermost zone is probably heavily altered andesine rock: the plagioclase is replaced by extremely fine-grained clay minerals which occur as a matrix forming about 70% of the rock, and which encloses subhedral biotite flakes up to 1 mm long, and minor amounts of magnetite. Accessory apatite and zircon are present.

Chemistry (Table 6)

Two samples, at 215.6 m and 187.8 m—are fairly similar to each other, except that the sample at 187.8 m contains 52% SiO_2, and that at 215.5 m has 45% SiO_2; the sample from 215.6 m has 5% Fe_2O_3, a reflection of the presence of magnetite. Otherwise, these rocks have moderate to low FeO and MgO. Compared with the harzburgites, they have high Al_2O_3, CaO, Na_2O, and K_2O—in fact, those elements that are not easily accommodated in the lattices of the harzburgite minerals.

The anorthite rock at 157.3 m is particularly rich in CaO and Al_2O_3 with small amounts of MgO; all the other oxides are very low in amount.

All three samples are undersaturated, and contain nepheline in their norms.

Mineral chemistry (Table 7)

The *plagioclase* at 215.5 m and 187.8 m is andesine; that at 157.3 m is anorthite. All three contain very little K_2O. *Phlogopite*, when compared with the examples in Deer, Howie and Zussman (1962), contain rather more SiO_2, Al_2O_3, total iron oxide and Na_2O, and somewhat lower MgO and K_2O. The *spinellid* at 215.5 m is virtually pure magnetite, containing only minor quantities of Ti, Al, Cr, and Mg. That at 157.3 m is a pleonaste; it contains only minor Fe^{+3} and trace quantities of Ti and Cr.

Table 6

Analyses and norms of the anorthositic Rocks, DDH C5.
Analyst: S.G.S. Australia Pty. Ltd.. Perth.

Depth	215·5 m	157·3 m	187·8 m
SiO_2	45·18	43·40	51·85
TiO_2	0·41	0·04	0·46
Al_2O_3	22·20	33·55	23·15
Fe_2O_3	5·04	0·26	0·35
Cr_2O_3	Tr	N.D.	0·02
FeO	3·67	0·45	2·53
MnO	0·05	0·01	0·02
MgO	5·04	1·72	6·54
NiO	0·03	0·01	0·04
CaO	6·18	17·03	5·85
Na_2O	4·99	0·97	5·12
K_2O	1·64	0·53	2·29
P_2O_5	0·35	0·17	0·09
Loss	2·42	1·90	1·98
Total	100·20	100·04	100·29
Ba	780	220	490
Co	46	N.D.	N.D.
Cr	27	N.D.	107
Ni	200	90	320
V	32	N.D.	<5
Zn	10	N.D.	N.D.
Ne	4·23	2·05	5·57
or	9·68	3·12	13·52
ab	34·39	4·57	33·03
an	28·34	83·36	28·45
c	1·82	0·83	1·83
ol—			
fo	8·79	3·01	11·41
fa	1·59	0·45	2·85
il	0·77	0·08	0·88
mt	7·32	0·37	0·51
ct	....	....	0·02
ap	0·84	0·40	0·20
Loss	2·42	1·90	1·98
Total	100·20	100·14	100·25

Discussion

The petrogenesis of the harzburgite and the feldspathic rocks must be considered in relation to the lherzolite (Morgan 1982), because all three form parts of the same ultramafic body.

Harzurgite-lherzolite relationship

The harzburgite occurs in the drill cores, stratigraphically, above the cyclic layering in the lherzolite. Hence, it cannot be regarded as an early crystal cumulate that preceded the lherzolite.

Three features, noted from drill hole data, and from outcrop on the western lake shore, strongly suggest that the harzburgite was emplaced after the lherzolite. First, mapping along the shore line showed the presence of three bodies of lherzolite. One is in contact with the gneissic country rock, but is partly enclosed by harzburgite. The others are entirely enclosed by harzburgite. They measure from 20 m by 25 m up to 50 m by 350 m, and are elongated parallel to the contact with the gneiss, They appear to be contact remnants and rafts isolated by the intrusion of the harzburgite.

Second are the occurrences at 58 m to 61 m and 149 m to 151 m both in DDH C5 of lherzolite, enclosed within harzburgite. These, following on from the field observations just described, are thought to be rafts of lherzolite intersected by the drilling.

Table 7

Mineral analyses, feldspar rocks, DDH C5.
Analyst: W. R. Morgan

	Plagioclase				Biotite				Spinellids			Zircon
Depth	157·3 m	187·8 m	215·5 m	Depth	157·3 m	187·8 m	215·5 m	Depth	157·3 m	215·5 m	Depth	187·8 m
SiO_2	44·39	57·08	58·14	SiO_2	40·23	44·75	41·87	TiO_2	0·03	0·01	SiO_2	30·98
Al_2O_3	35·26	26·33	25·68	TiO_2	0·34	1·91	2·17	Al_2O_3	63·49	0·12	ZrO_2	66·21
Fe_2O_3	0·14	0·20	0·15	Al_2O_3	20·75	14·69	16·71	Cr_2O_3	0·02	0·05	TiO_2	0·03
MgO	Nil	0·03	0·02	Cr_2O_3	Nil	0·07	0·01	Fe_2O_3	2·21	68·90	Al_2O_3	1·13
CaO	19·66	8·52	8·59	FeO	4·81	8·92	7·97	FeO	17·87	31·42	Fe_2O_3	0·30
Na_2O	0·84	6·90	6·58	MnO	0·02	0·07	0·14	MgO	15·45	0·02	MnO	0·03
KO	0·01	0·02	0·06	NiO	Nil	0·08	Nil				MgO	0·01
				MgO	23·78	20·14	20·82				CaO	0·15
	100·31	99·11	99·00	CaO	0·03	0·01	Nil		99·07	100·52	ThO_2	0·09
				Na_2O	2·18	1·30	1·33				P_2O_5	0·07
				K_2O	7·10	8·20	8·19					
					99·24	100·14	99·21					99·00

Number of ions

	32 oxygens				24 oxygens				32 oxygens			16 oxygens
Si	8·202	10·330	10·481	Si	5·403	6·059	5·725	Al	15·674	·043	Si	3·833
Al	7·681	5·618	5·458	Al^{IV}	2·597	1·941	2·275	Cr	·003	·012	Zr	3·995
Fe^{+3}	·019	·028	·020	Al^{VI}	·688	·407	·419	Fe^{+3}	·348	15·987	Ti	·003
Mg	..	·008	·004	Ti	·034	·195	·223	Ti	·005	·002	Al	·165
Ca	3·893	1·652	1·660	Cr	..	·001	·001	Mg	4·822	·009	Fe^{+3}	·028
Na	·302	2·421	2·301	Fe^{+2}	·540	1·739	1·822	Fe^{+2}	3·129	8·057	Mn	·003
K	·002	·004	·013	Mn	·002	·008	·016				Mg	·002
				Ni		·008					Ca	·020
Ab	7·2	59·4	57·9	Mg	4·760	4·070	4·243				Th	·003
An	92·7	40·5	41·8	Ca	·004	·002					P	·007
Or	·1	0·1	0·3	Na	·568	·342	·353					
				K	1·217	1·419	1·428					

Third, the radial pyroxene harzburgite, adjacent to the Harzburgite-lherzolite contact in DDH C4 and C5 is believed to be a contact facies, caused partly by the strain and physical disruption of near solidfied harzburgite magma during emplacement against lherzolite. It is suspected that the subradial structures of unstrained orthopyroxene evolved by recrystallization due, perhaps, to heat derived from solid, but still hot, lherzolite. This would imply that there was no great time gap between the emplacement of the lherzolite and the harzburgite.

Harzburgite-gneiss relationship

The gneissic country rocks occur at the tops of the drill cores in DDH C2 and C4. However, the contact relations exposed by the drilling are inconclusive (Morgan 1982). However, evidence from the very poor lake shore exposures show that the harzburgite intrudes the gneisses. Detailed mapping carried out by geology students from the Western Australian Institute of Technology, under the author's direction, at the north-west shore showed a trail of four bodies of andradite-salite-anorthite rock extending over 200 m within strongly serpentinized harzburgite, aligned parallel to the contact with the gneiss.

Modal and chemical analyses of this material, together with electron microprobe analyses of the constitutent minerals, are given in Table 8. From these data, it is considered that these bodies are xenoliths of calc-silicate metasedimentary rocks.

Harzburgite emplacement

The megacrystic harzburgite

In this unit, the large orthopyroxene grains show the results of considerable deformation—lattice strain, mosaic substructure, to complete polygonization—in the northerly diamond drill core (DDH C5). It could be argued that this unit was emplaced prior to tectonism, with the deformation resulting from the tectonism. However, the megacrysts in DDH C3 (the most southerly drill hole) are euhedral and unstrained, which strongly suggests that they were phenocrysts in a magma that was emplaced after tectonism. Their deformation in the northerly cores thus suggests that the ultramafic magma was crystallizing during intrusion, with the still largely liquid material in the vicinity of DDH C3 pushing northwards against partly to mostly crystallized magma in the vicinity of DDH C4 and, more particularly, DDH C5.

The lenticular-textured harzburgite

The origin of this unit is much more difficult to explain, principally because its relationship to the megacrystic harzburgite is unknown. In composition, it is rather more Mg-rich than the megacrystic harzburgite, being closer to the alpine-type ultramafics. However, the ultramafic body as a whole—including the lherzolite and the megacrystic harzburgite—is certainly not alpine-type.

An explanation that could satisfy both its textural characteristics and its more magnesian character is to regard it as an early-crystallized part of the harzburgite, chilled against the relatively cool gneisses. The zone containing the lenticles, which, in DDHC4, extends 80 m to 105 m depth, would

Table 8

Xenolithic calc-silicate rock: modal and chemical analyses of the rock, and chemical analyses of its constituent minerals

Rock

Mode				*Chemical			
Anorthite	....	....	53·2	SiO$_2$	....	....	43·3
Salite	....	....	27·1	TiO$_2$	....	....	1·25
Andradite	....	....	20·2	Al$_2$O$_3$	....	....	18·5
				Fe$_2$O$_3$	....	....	5·18
			100·0	FeO	....	....	3·05
				MnO	....	....	0·26
				MgO	....	....	4·25
				CaO	....	....	22·9
				Na$_2$O	....	....	0·36
				K$_2$O	....	....	0·02
				LOI	....	....	0·49
				Total	....	....	99·56

Minerals

			§Andradite	§Salite	§Anorthite
SiO$_2$	....	....	36·18	49·96	44·24
TiO$_2$	....	....	1·04	0·12	0·01
Al$_2$O$_3$	....	....	6·19	2·76	33·91
Cr$_2$O$_3$	....	....	0·08	0·01	0·01
Fe$_2$O$_3$	....	....	21·47†		0·45†
FeO	....	....	..	11·44‡	....
MnO	....	....	0·57	0·55	0·04
NiO	....	....	0·01	0·01	0·02
MgO	....	....	0·29	10·67	0·03
CaO	....	....	32·98	23·27	19·70
Na$_2$O	....	....	0·24	0·32	0·76
K$_2$O	....	....	Nil	0·02	0·02
Total	....	....	99·06	99·13	99·18

Numbers of ions:			24 oxygens	6 oxygens	32 oxygens
Si	....	....	5·960	1·919	8·264
Al^{iv}	....	....	0·040	0·081	7·539
Al^{vi}	....	....	1·150	0·043	....
Ti	....	....	0·139	0·004	0·002
Fe	....	....	2·635†	0·368‡	0·064†
Cr	....	....	0·098	0·001	0·002
Mn	....	....	0·792	0·018	0·007
Ni	....	....	0·001	Tr	0·003
Mg	....	....	0·710	0·611	0·008
Ca	....	....	5·822	0·958	3·961
Na	....	....	0·077	0·024	0·277
K	....	....	....	0·001	0·005

*Analyst: S.G.S. Australia Pty. Ltd. Perth. §Analyst: W. R. Morgan, W.A.I.T. †Total iron calculated as Fe$_2$0$_3$(Fe^{+3}). ‡Total iron calculated as FeO (Fe^{+2})

represent deformed, mostly crystallized material dragged by the motion of the more liquid megacrystic harzburgite. The gneissic country rock, at the height of granulite metamorphism, would have had temperatures of around 760° to 900°C (Hewins 1975). A partly crystallized harzburgite magma with, say, 20% to 30% crystals, would have a temperature between 1 400-1 700°C (Ito and Kennedy 1967).

However, this argument suffers because there is nothing chemically or texturally equivalent to the lenticular-textured harzburgite adjacent to the lherzolite. It may be therefore, that the lenticular-textured harburgite represents a third intrusive body, younger that the lherzolite, but whose age relationship to the megacrystic harzburgite is not known.

Interpretation of textures

The writer (Morgan 1982) discussed the petrography of the lherzolite unit in terms of metamorphic textures superimposed on relic igneous structures. In the discussions above, he has stressed the igneous emplacement of the harzburgite, using the deformation of megacrysts and other features to support his argument. Nevertheless, apart from the megacrysts, textural features of the harzburgite have a metamorphic appearance. Even in rocks where the megacrysts display strong straining and sub-mosaic structures, the matrix grains are entirely unstrained, and have curvilinear to straight-line boundaries, i.e., the grain shapes range from amoeboid to polygonal.

The causes of the metamorphic texture are probably two-fold. First, the effect of the heat of the intrusion itself annealing matrix crystals strained whilst emplacement of the crystal mush was taking place. Second, the effect of the continuing heat of the regional metamorphism of the country rocks enclosing the body. Morgan (1982) believes that the lherzolite unit was intruded during granulite facies metamorphism of the country rocks, after the completion of tectonic deformation; the writer suggests, earlier in this report, that the harzburgite unit was emplaced only a short time after the lherzolite, i.e., during the metamorphism.

The feldspathic rocks

Age relationships

The feldspathic rocks and veins of granite material were emplaced after the harzburgite. The granitic material intrudes both the lherzolite and the harzburgite. The feldspathic rocks occur only in the harzburgite. Both have hydrated and possibly metasomatized the ultramafic body. The relationship between the granitic veins and the feldspathic rocks is not known. However, for reasons given below, it is possible that the feldspathic rocks are related to the ultramafic body. The granitic veins are probably related to a much younger period of granitic emplacement (eg. Wilson 1958).

Emplacement

The feldspathic rocks are very minor occurrences in the harzburgite, and their origin is problematical. Prider (1945) referred to andesinites within granulite facies ultramafics at Dangin as "segregations". If that is their occurrence here, they could be interpreted in one of two ways.

First, they could represent a late stage "aplitic pegmatitic" phase of the ultramafic, emplaced on primary cooling joints in the harzburgite. The feldspathic rocks contain elements (Al, Ca, Na, K, Zr), and volatiles that are incompatible with the lattice sites of orthopyroxene and olivine. Their emplacement would have been accompanied by hydration and potash metasomatism of the harzburgite.

A second view is that, petrogenitically, they are entirely unrelated to the harzburgite. Granulite facies rocks in the Western Australian wheat belt are regarded as xenolithic masses fragmented by subsequent granitoid invasion (Wilson 1958, 1959; Prider 1945, Davidson 1968). Potash metasomatism associated with the feldspathic rocks, along with the presence of zircon, suggest that they represent a metasomatism induced by the granitoid invasion which took place about 2 800 m.y. ago (Wilson 1958).

Concluding remarks

The diamond drill cores have given us only a glimpse of what must be a complex ultramafic body. Because of extremely poor exposures in the field, really very little is known of the ultramafic-country rock relationships, or of the relationships of the consitutent members of the ultramafic body. In fact, there may well be other units in the ultramafic, besides harzburgite and lherzolite, not exposed by the drilling. Hence, any conclusions drawn from this, and the author's previous study (Morgan 1982) must be tenuous.

The relationship between the lherzolite and the harzburgite is not clear. The lherzolite, from chemical and modal evidence (Morgan 1982) appears to be a series of cumulate-rocks resulting from the differentiation of a basaltic magma. On the other hand, the slightly younger harzburgite seems to be the result of the *in situ crystallization* of an ultramafic magma. Hence, there can be no intimate petrogenic relationship between them: one is not derived from the other. Yet they are intimately related in time and space, hence they must both have been derived from the same source during the course of a continuing geological event.

One might guess that rising upper mantle temperatures resulted, first, in the generation of tholeiitic magma as a parent of the lherzolite, followed by the melting of much more refractory material, producing the harzburgite. This postulated upper mantle "hot spot" may well be the reason for the granulite facies metamorphism in the area, and could be an event in a long-continued process of sedimentation, igneous activity, tectonism, and metamorphism that was ultimately completed with the emplacement of granitoids about 2 800 m.y. ago.

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